Influence of Waste Lubrication Oil Combustion on Emissions

B. O. Owiti1*, H. M. Ndiritu1 and B. B. Gathitu2

Abstract—Rising Energy prices across many regions have led to major shifts in energy supply sources and the overall trade balances. Fossil fuel faces the danger of being depleted and at the same time it degrades the environment. Fluctuating oil prices also increases the cost of running power plants that are based on fossil fuels. Global environmental protection requirements coupled with concern for long-term and sustainable energy supply necessitates exploration and exploitation of alternative fuel sources to supplement and avoid overreliance on already existing sources. Waste lubrication oil is one such source. It is a major output from lubrication process in transportation, industries and power generation sectors among others. With further industrialization and population growth especially the middle class, the amount of waste lubrication oil is set to increase significantly thereby making it a potential source of energy for process heating. There is also a need to establish safe mechanisms of recycling and utilizing this waste oil to protect the environment from disposal pollution problems. Waste lubrication oil can be burnt under flow regulations using waste oil burner to minimize combustion emissions.

Keywords—waste lubrication oil, power generation, combustion emission, disposal.

I. INTRODUCTION

Major problems associated with energy supply for industrial development include: climate change, pollution and energy insecurity. To be able to address these problems, huge changes in energy infrastructure must be made [1]. Hydroelectricity is the main form of renewable source of energy worldwide. In Africa, it is recorded that effects of climate change affect severely Hydroelectric Power (HEP) plants more so in areas of low annual rainfall. Climate change results in increasingly unpredictable weather patterns making HEP plants ineffective and unreliable due to reduced dam reservoir inflows to non-sustainable levels during dry seasons [2]. In Kenya, energy deficit is experienced in form of frequent power rationing and outages. HEP highly relied on as the main renewable energy source in the country decreases in output annually due to constantly reducing rainfall and droughts. Kenya’s hydropower base contributes about 55% of national energy requirements. This contribution is endangered by rainfall decline and therefore the nation may be forced to explore other energy sources to sustain its industrial operations. Masinga dam, one of the Seven Forks dams, has its HEP output decreasing yearly due to decline in average dam water level at the rate of 0.58 m annually [2]. It is expected that global energy demand will double by the year 2050 even with some improvements in energy efficiency realized. This is inevitable due to expected global population growth, global economic growth, continued urbanization and increased demand on mobility and other energy dependent services. World energy demand is growing much faster than expected leading to a widening gap between supply and demand for electric energy [3]. Depletion, increasing demand and price of petroleum prompted extensive research worldwide on alternative energy sources for internal combustion engines and other combustion processes [4]. This therefore, calls for the need to diversify energy generation by utilizing more of the existing sources as well as exploring new energy sources. Waste Lubrication Oil (WLO) has quite high energy content but is very much underutilized especially in the area of power generation. It originates from various sources like automotive sector, hydraulic systems, rail locomotives, industrial sector, turbines, and transformers among others [5]. One major and significant characteristic of WLO is that it contains both chemical and physical impurities and as such requires re-refining to enable its recycling and/or reuse [6] - [7]. Kenya’s economy is actively driven by energy from wood fuel, petroleum and electricity excluding solar energy which is widely used for drying purposes [8].

There have been increased efforts to reduce overreliance on petroleum fuel for energy generation and in transportation and attention is shifting to alternative fuels [9]. A lot of energy goes untapped from WLO when it is thrown away as a means of disposal as is the practice in many areas. Conventional methods of disposing off WLO are very hazardous and quite harmful to both land and water bodies. Arumugam, Veeraraja and Esakkimuthu [10] propose waste oils from automobiles, industries and cooking as energy source to supplement energy demand due to their high heat values. If proper measures and regulations regarding combustion of WLO are observed then WLO can be a major source of energy. Combustion emissions of a WLO burner are determined by the burner operating conditions these emissions are mainly carbon monoxide (CO) and carbon dioxide (CO2), unburnt hydrocarbon (UHC) and oxides of nitrogen (NOx) i.e. NO and NO2.

This paper presents effects of varying combustion reactants flow rates (fuel and oxidizing air) on combustion emissions (CO and UHC) and CO2.
A. Carbon Monoxide and Carbon Dioxide

When a complete combustion process occurs, the normal products of combustion that result are CO₂ and water vapour. An incomplete combustion will result into formation of CO and other unburnt fuel particles as combustion emissions. CO emissions are more likely to result during rich mixture conditions. It is an intermediate species formed from reaction of oxygen atom with carbon in the fuel. First, oxygen molecule is broken into oxygen atoms with the help of an energetic third body, M. These atoms then combine with carbon to form CO as illustrated in Equations 1 and 2 below.

\[ O_2 + M \rightarrow O + O + M \] (1)

\[ C + O + M \rightarrow CO + M \] (2)

If sufficient oxygen (O₂) required for complete combustion of a given fuel is present then CO will be completely oxidized to CO₂ [11]. This is illustrated using Equation 3.

\[ CO + O + M \rightarrow CO_2 + M \] (3)

B. Unburnt Hydrocarbon (UHC)

During combustion UHC result due to many reasons. Fuel rich mixtures is one of the reasons for UHC emission. This means less O₂ is available for for complete fuel oxidation and as such some of the fuel will leave the combustion chamber unburnt. In regions of the flame near the combustion chamber surfaces heat lost through the chamber walls is greater than the heat required to sustain the flame. This condition causes areas of quenched flame where hydrocarbons are left unburnt. Also in many cases combustion chamber contain gaps and services that hinder flame propagation. UHC usually build up as extended residence time in the combustion chamber at high temperatures [11].

\[ N + O_2 \rightarrow NO + O \] (6)

If combustion temperatures and residence time in the combustion chamber are minimized and appropriate amount of air is used during combustion then NOx emissions can be minimized as well.

II. MATERIALS AND METHODS

Waste in general refers to any material rejected as unfit for further use [12]. Waste Oil (WO) is defined as any oil that has been refined from crude oil or mixtures containing synthetic oil that has been used and is therefore contaminated [13]. The main chemical composition of WLO include carbon (C), hydrogen (H) and oxygen (O) elements. Others elements that appear in traces are nitrogen (N) and sulphur (S). It also contains ash and water that may have sipped into it through leaking seals during combustion process in engines. Therefore its major elements involved in a combustion reaction are C and H and O₂ is required as an oxidizer. The others that appear in traces are dropped and hence its chemical equation can be determined. Table I below represents WLO chemical compositions as posted by Gomez-Rico, Martín-Gullon, Fullana, Conesa and Font [14].

<table>
<thead>
<tr>
<th>Constituents</th>
<th>% weight</th>
<th>Element</th>
<th>Atomic wt (kg/kg mole)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>85.35</td>
<td>C</td>
<td>12</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>13.25</td>
<td>H₂</td>
<td>2</td>
</tr>
<tr>
<td>Oxygen</td>
<td>0.09</td>
<td>O₂</td>
<td>32</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>0.9</td>
<td>N₂</td>
<td>28</td>
</tr>
<tr>
<td>Sulphur</td>
<td>0.46</td>
<td>S</td>
<td>32</td>
</tr>
<tr>
<td>H₂O</td>
<td></td>
<td></td>
<td>18</td>
</tr>
<tr>
<td>CO₂</td>
<td></td>
<td></td>
<td>44</td>
</tr>
<tr>
<td>SO₂</td>
<td></td>
<td></td>
<td>64</td>
</tr>
<tr>
<td>Ash</td>
<td>0.05</td>
<td></td>
<td>-</td>
</tr>
</tbody>
</table>

Lower heating value (LHV) for this waste lubrication oil was determined as 48.17 MJ/kg. The values in Table I above were used to determine moles for each fuel constituent and hence WLO chemical formula expressed as \( C_{7.104}H_{13.25}O_{0.006} \). This expression of WLO chemical formula is normalized as shown.

\[
\left( \begin{array}{c}
7.104 \, C \\
13.25 \, H \\
0.006 \, O
\end{array} \right) = 7.104 \left( \begin{array}{c}
1.865 \, C \\
0.0008 \, H \\
0.0008 \, O
\end{array} \right)
\]

Normalized WLO chemical formula is therefore expressed as \( CH_{1.865}O_{0.0008} \). A balanced Stoichiometric Reaction between WLO and air is therefore given by Equation 7 below:

\[
CH_{1.865}O_{0.0008} + 1.466O_2 \rightarrow CO_2 + 0.933H_2O
\] (7)
Properties of WLO as experimentally determined were as shown in Table II below.

**TABLE II
PROPERTIES OF WASTE LUBRICATION OIL**

<table>
<thead>
<tr>
<th>Test</th>
<th>Mean Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHV (pure diesel engine WLO)</td>
<td>43.39 MJ/kg</td>
</tr>
<tr>
<td>LHV (mixture of diesel and petrol engine WLO)</td>
<td>42.98 MJ/kg</td>
</tr>
<tr>
<td>Moisture content</td>
<td>0 %</td>
</tr>
<tr>
<td>Density</td>
<td>875.9 kg/m³</td>
</tr>
<tr>
<td>Relative density</td>
<td>0.8759</td>
</tr>
<tr>
<td>Kinematic viscosity at 25⁰C</td>
<td>1371.5 Centistoke</td>
</tr>
<tr>
<td>Insoluble residue</td>
<td>0.056 %</td>
</tr>
<tr>
<td>Flash point</td>
<td>202⁰C</td>
</tr>
<tr>
<td>Ash content</td>
<td>0.765 %</td>
</tr>
</tbody>
</table>

WLO fuel was burnt at three different flow rates of 5.05 kg/h, 5.65 kg/h and 6.25 kg/h and excess air (EA) of 12 %, 20% and 30% EA).

**A. 5.05 kg/h Fuel Flow Rate**  
Fuel mass flow rate, \( \dot{m}_{fuel} \) in kg/h, is used to determine flow rate of each of carbon fuel and oxygen as 1.403 g/s.

Carbon mass flow rate, \( \dot{m}_{fuel(C)} \), is given by Equation 9 below.

\[
\dot{m}_{fuel(C)} = 0.8525 \times \dot{m}_{fuel} 
\]

\[
= 0.8525 \times 1.403 = 1.196 g/s
\]

And Fuel carbon molar flow rate, \( \dot{n}_{fuel(C)} \), is thus deduced as:

\[
\dot{n}_{fuel(C)} = \frac{\dot{m}_{fuel(C)}}{\text{molar weight of carbon}} 
\]

\[
= \frac{1.196 g/s}{12 g/mole} = 0.0997 \text{ moles/s} \approx 0.1 \text{ moles/s}
\]

Oxygen molar flow rate is therefore calculated as shown below.

\[
\dot{n}_{fuel(O_2)} = \dot{n}_{fuel(C)} \times SC_{O_2} = 0.1 \times (1.466 + 0.0008)
\]

\[
= 0.14668 \text{ moles/s} \approx 0.147 \text{ moles/s}
\]

where: \( SC_{O_2} \) is the amount of oxygen required for stoichiometric combustion to take place.

Oxygen volume flow rate at room temperature and pressure (RTP), \( \dot{V}_{O_2@RTP} \) is given as:

\[
\dot{V}_{O_2@RTP} = 24 L/s \times \dot{n}_{fuel(O_2)}
\]

\[
= 24 L/mole \times 0.147 \text{ moles/s} = 3.52 L/s
\]

24 L/mole is used in the above equation because it is the capacity of atmospheric air at standard conditions.

**B. 5.65 kg/h Fuel Flow Rate**

\[
5.65 \text{ kg/h} = 1.569 g/s
\]

\[
\dot{m}_{fuel(C)} = 0.8525 \times 1.569 = 1.338 g/s
\]

\[
\dot{n}_{fuel(C)} = \frac{1.338 g/s}{12 g/mole} = 0.111 \text{ moles/s}
\]

\[
\dot{n}_{fuel(O_2)} = 0.111 \times 1.4668 = 0.164 \text{ moles/s}
\]

\[
\dot{V}_{O_2@RTP} = 24 L/mole \times 0.164 \text{ moles/s} = 3.925 L/s
\]

\[
\dot{V}_{air@RTP} = \frac{3.925}{0.21} = 18.691 L/s = 1.121 m³/min
\]

**C. 6.25 kg/h Fuel Flow Rate**

\[
6.25 \text{ kg/h} = 1.736 g/s
\]

\[
\dot{m}_{fuel(C)} = 0.8525 \times 1.736 = 1.48 g/s
\]

\[
\dot{n}_{fuel(C)} = \frac{1.48 g/s}{12 g/mole} = 0.123 \text{ moles/s}
\]

\[
\dot{n}_{fuel(O_2)} = 0.123 \times 1.4668 = 0.181 \text{ moles/s}
\]

\[
\dot{V}_{O_2@RTP} = 24 L/mole \times 0.181 \text{ moles/s} = 4.342 L/s
\]

\[
\dot{V}_{air@RTP} = \frac{4.342}{0.21} = 20.675 L/s = 1.241 m³/min
\]
III. EXPERIMENTAL SETUP
Waste Lubrication Oil burner having reactants flow regulators was used in this study. This burner had a fuel pump with variable flow pressure up to a maximum of 15 bar, variable flow air supply blower, fuel atomizing nozzle of 60° spray angle and atomization rate of 5.68 L/h. Figures 1 and 2 below show schematic and pictorial views respectively of the setup used during the experiments.

IV. RESULTS AND DISCUSSIONS
A. Burner Combustion Emissions
WLO burner emissions were monitored at minimum fuel flow rate that initiated ignition, maximum fuel flow rate and an intermediate flow rate with EA of 12%, 20% and 30% for each test. 30% EA was the maximum used since too much EA in a combustion process results in the unused excess oxygen carrying away with it some heat energy thereby reducing system’s thermal efficiency. The following emissions were monitored and recorded:

1) Carbon Monoxide: Carbon monoxide emissions were recorded and added up for each EA value and fuel flow rate to get average CO emission from the combustion process. Graphs of CO emission concentration versus fuel flow rates at various EA values were then plotted as shown in Figure 3.

CO emission increased with increasing fuel flow rate but decreased with an increase in amount of excess air with 30% excess air combustion having the least amount of CO. CO is an intermediate species formed before CO$_2$ in a hydrocarbon combustion. It is formed once fuel and intermediate hydrocarbon fragments are consumed as shown in Equations 1 and 2 above.

CO is a toxic gas and therefore large exposure to its emission can result into significant toxicity of the central nervous system, heart and eventually death [15]. The highest CO emission was recorded as 0.0725% volume at fuel flow rate of 6.25 kg/h and 12% EA which was also equivalent to 725 ppm of CO emission. This was attributed to the fact that there was an increase in fuel flow rate allowing large amount of fuel to pass into combustion chamber at any given time. Excess air being minimum and fuel quantity maximum, a fuel rich combustion resulted and hence there was oxygen deficit to fully oxidize CO species formed to CO$_2$. Therefore, much
of this CO left combustion chamber to the exhaust as emission.

The CO emission concentration depicted a marked reduction between the maximum and minimum EA used during combustion with fuel flowing at a maximum rate of 6.25 kg/hr. CO is a toxic gas and its reduction is therefore desirable and highly recommended. CO emission reduction achieved in burning WLO was 44.83%. This verified the fact that EA is required for a nearly complete combustion to occur. Lou, Huang and Yang [16] studied emission concentration in a combustion process and reported that in a combustion process, CO concentration decreased as flame temperature increased with EA of upto 25% used. Excess air can improve fuel oxidation, improve combustion efficiency as well as lower flue gas temperature. According to experiments done by Lou, Huang and Yang on municipal solid waste combustion, the exit flame temperature increased to a maximum of 650 °C with EA upto 30% after which it started decreasing.

Even with much excess air used in a combustion process a perfectly complete combustion can still not be achieved. A complete combustion can never be achieved with both stoichiometric air and excess air simply because of two main reasons:

- It is not possible to create enough turbulent to facilitate sufficient fuel and oxidizer mixing.
- The mixing time is usually very short which may not warrant complete and sufficient mixing of fuel and oxidizer.

2) Carbon Dioxide: CO₂ is one of the by-products of a combustion process along side water vapour. The higher the volume of CO₂ generated the higher the efficiency of a combustion process. It can therefore be used as an indicator of a complete combustion. Figure 4 below shows variations of CO₂ emissions with fuel flow rates at various EA values.

An excess air of 12% and fuel flow rate of 5.05 kg/hr resulted in formation of maximum CO₂ as product of combustion. This was due to the fact that more excess air relative to the amount of fuel supplied resulted to a lean combustion. More intermediate species (CO) formed was oxidized to CO₂ by oxygen atoms formed during chain initiation process. Excess air facilitated more fuel oxidation to a near complete combustion and more CO₂ generation in the process. CO₂ generation decreased with increasing excess air. This was as a result of the extra air supplied cooling the combustion system by absorbing heat and transporting it out in the flue gases thereby reducing combustion temperatures. Cooling contributed in slowing down the reaction thereby reducing the amount of combustion byproducts generated. Cooling also slowed down CO oxidation to CO₂ as this process is accelerated at temperatures above 1100 K. Excess air also diluted flue gases further contributing to reduction in CO₂ concentration. A maximum difference of 11.99% CO₂ emission was achieved between the minimum and maximum SR values at fuel flow rate of 6.25 kg/hr.

3) Unburnt Hydrocarbon (UHC): Complete and efficient combustion is quite difficult to achieve. It is therefore expected that some fuel particles will leave combustion chamber to the exhaust unburnt to form UHC. Figure 5 shows UHC concentration results for 12% EA, 20% EA and 30% EA at various fuel flow rates.

Emissions comparison graphs for each EA value are presented.
in Figures 6, 7 and 8 below. From all the graphs, it can be observed that CO\textsubscript{2} emission reduced for all EA values while both CO and UHC increased with increasing EA.

![Graph of CO\textsubscript{2}, CO, and UHC emissions vs. fuel flow rate for SR1.12, SR1.20, and SR1.30](images/graph.png)

V. CONCLUSION

Combustion tests were done for WLO and emissions monitored at various fuel flow rates and EA supply. From results achieved, the following conclusions are made:

Combustion emissions can be regulated by varying both fuel flow and combustion air supply. The highest CO emission was recorded at 0.0725 % volume at a fuel flow rate of 6.25 kg/h and 12% EA. Maximum difference in CO\textsubscript{2} emission was achieved at a fuel flow rate of 6.25 kg/h. This was the difference between CO\textsubscript{2} emissions at 30% EA and 12% EA. The percent difference was got as 11.99%. Percent reduction in UHC concentration were recorded as 18.63%, 25.64% and 18.69% for 5.05 kg/h, 5.65 kg/h and 6.25 kg/h fuel flow rates respectively. Maximum UHC recorded was 183.25 ppm at 12% EA and fuel flow rate of 6.25 kg/h.

From the comparison graphs, CO\textsubscript{2} emission reduced for all EA values while UHC emission increased with increasing EA. CO emission also varied directly with fuel flow rate for all EA values.

Emissions (CO\textsubscript{2}, CO and UHC) formation were mainly affected by excess air and combustion process efficiency (level of fuel atomization). An intermediate species, CO, was formed from reaction of fuel carbon with oxygen radical generated during chain initiation process. This CO then reacted further with more oxygen radicals to form CO\textsubscript{2}. More excess air implied more radical formation for more CO\textsubscript{2} generation. Conversion of more CO to CO\textsubscript{2} reduced CO amount in the exhaust gases but increased CO\textsubscript{2} amount generated. This is the reason why CO\textsubscript{2} and CO graphs have an indirect relation. Both CO and UHC resulted due to incomplete combustion. An increase in CO emission in a combustion process was accompanied by an increase in UHC emission. UHC was also influenced by flame speed and fuel reaction speed. Higher fuel reaction speed than flame speed meant that more fuel passed through the combustion chamber unburnt to constitute UHC at the exhaust. Higher fuel flow rates at constant excess air value implied a rich fuel combustion and hence more CO and UHC generated. It is therefore concluded that CO\textsubscript{2}, CO and UHC emissions generation are dependent on one another.

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